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## **COMPARISON OF SHIP LAUNCHING EVALUATION METHODS**

### **Summary**

Ship launching is a complex event, particularly when uncommon ship structures are in concern. Due to that, shipyards perform pre-launching calculations to determine ship's speed, acceleration, traveling distance, maximum draft etc. These calculations are reliable and virtually all of the ship launchings are successful. Due to the same reason, they are rarely verified. An attempt is made here to compare different ship launching evaluation methods. Particular launching event, occurred in Uljanik shipyard, was recorded by high-precision differential GPS (DGPS) measuring device and a video camera. Obtained information were analyzed and compared with shipyard and theory based ship launching calculations. A margin for errors was detected and results discussed.

*Key words:*        *longitudinal ship launching, DGPS record, launching calculation*

## **USPOREDBA METODA ZA PROCJENU PORINUĆA BRODA**

### **Sažetak**

Porinuće broda složen je događaj, a pogotovo kada su u pitanju netipični brodovi. Iz tog razloga brodogradilišta obavljaju proračune porinuća kako bi odredili brzine i ubrzanja broda, otplov broda, najveći gaz i drugo. Ti su proračuni pouzdani i praktički sva porinuća izvede se uspješno. U ovom radu prikazana je usporedba različitih metoda za procjenu porinuća broda. Tijekom nedavnog porinuća u brodogradilištu Uljanik na brodu su izvedena mjerenja pomoću preciznog diferencijalnog DGPS uređaja (DGPS), a učinjen je i video zapis. Prikupljeni podaci uspoređeni su s podacima proračuna brodogradilišta i teorijskim proračunom. Uočena odstupanja su analizirana i raspravljena.

*Ključne riječi:*    *uzdužno porinuće broda, DGPS mjerenje, proračun porinuća*

## 1. Introduction

Ship launching is an important event representing the beginning of the ship's life. Successful launching lays the ship smoothly in the water and launching ends when the ship stops and floats freely. Launching of the ship may be either longitudinal or side launching. Only the former will be considered in this article as longitudinal launching is common in Croatian and many other seaside shipyards.

Launching may be described by methods based on solution of differential equations of ship dynamics or the energy balance methods. Three different methods will be used to perform ship launching calculation for a study-case ship, built and launched in Uljanik shipyard. In addition, precise measurement of ship translation was made onboard the ship during launching. In this way, predicted and real-world ship dynamics can be compared.

The motivation for this research is summarized in the following way. Recent research in ship launching are absent from the contemporary literature, probably due to the fact that theoretical background of the launching process is established decades ago. This may consequently limit the interest in launching technology and related problems in academia. At the same time, recent deep and significant changes in shipbuilding market forces domestic shipyards toward building of a complex ships of new type, as for example dredgers. Along with other technology challenges, launching of such ships is connected with the certain unknowns or at least with the lack of previous experience. Again using dredgers example, these ships are launched bow-first which is opposite of classic stern-first launching. Today, modern measurement and recording tools are available for ship launching monitoring (GPS, video) providing numerous valuable data that can be used for evaluation of launching success. Finally, state-of-the art numerical tools, such as nonlinear FEM, are available for complete analysis of ship dynamics during launching. Although numerical analysis will not be presented here, detailed analytical solution and precise real-life measurement are prerequisites for calibration of numerical models, calculation and analysis. By combining theory, measurements and numerical analysis, knowledge on ship launching may be mastered to meet future challenges.

Theoretical mechanics and hydromechanics analysis of ship launching is established decades ago. No attempt will be made here to present historical development of ship launching technology. Analysis will be limited by methods presented by prof. Josip Uršić (differential equation method and energy method) and prof. V. Semyonov-Tyan-Shansky (differential equation method). These methods have common elements but differ in some assumptions, simplifications and solution methodology. These differences will be commented. In each case, four stages or phases of ship launching is clearly distinguished: phase 1 - commencement of motion, phase 2 – ship enters into water, phase 3 - stern lifting and phase 4 – dropping of the slipway. The analysis within each method is divided accordingly. In addition, Uljanik in-house made calculation will be compared with the three analytical solutions mentioned.

The obtained results will then be compared with DGPS track and video record of ship movement. Former is a high precision position measurement technique. Later is a video analysis tool which has the advantage of being simple to use, cheap and informative. While analytical (and numerical) techniques aim to predict the ship launching parameters it is measurement techniques only that can evaluate the success of such predictions.

## 2. Launching study case

The launching of Uljanik build 483 represent a study case in this article. Ship was successfully launched on February 19th, 2011. The name of the ship is Grande Costa d'Avorio and it is 24800 tons multipurpose Ro-Pax built for Grimaldi Group. The main ship particulars are: length 210m, beam 32m and height 21.5m. Ship cruising speed of 21.9 knots is delivered by its 19040kW main engine. Figure 1 shows the ship ready for delivery and Figure 2 shows the ship under construction on the slipway.



**Fig. 1** Grande Costa d'Avorio

**Slika 1.** Grande Costa d'Avorio



**Fig. 2** Grande Costa d'Avorio on the slipway

**Slika 2.** Grande Costa d'Avorio na navozu

The movement of the ship was recorded using precise DGPS measurement device and inclinometer by Brodarski institut. At the same time, a video recording of the event was captured from the nearby location. Figure 3 shows satellite image of Uljanik shipyard, with straight line representing ship trajectory after launching from Uljanik slipway 1. Triangle shaped curves on the same figure indicate viewing angle during camera recording. DGPS measurement location is indicated by the arrow on Figure 3 (right).

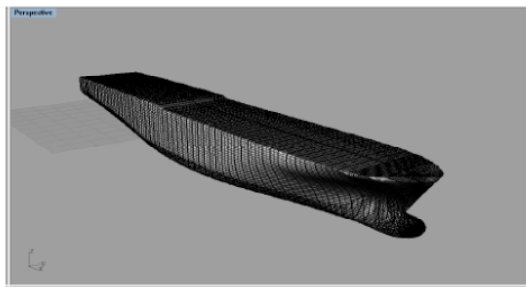


**Fig. 3** Ship trajectory and camera angle (left) and Grande Costa d'Avorio launching (right)

**Slika 3.** Putanja broda i kut snimanja (lijevo) i porinuće Grande Costa d'Avorio (desno)

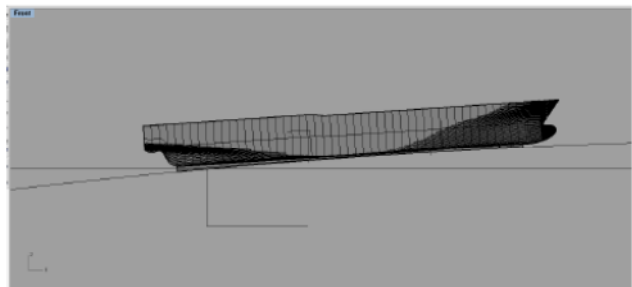
### 3. Ship CAD model

All the data needed for launching calculation was kindly provided by Uljanik shipyard. This includes: numerical readout of the ship hull form, frame lines and water-level lines drawings. Out of this, a ship model was reconstructed using CAD software. Figure 4 presents ship hull model and figure 5 presents the same model adjusted precisely on the slipway geometry.



**Fig. 4** Ship hull model

**Slika 4.** Model trupa broda



**Fig. 5** Ship model and slipway geometry

**Slika 5.** Model broda i geometrija navoza

CAD model is used to obtain hydrostatic and geometrical properties needed for launching calculation such as. Required data was collected for each launching phase. The procedure is briefly described here.

Phase 1. Ship model is set on its initial position which is defined, among other parameters, by 3.40 degree angle between weight vector and slipway normal vector. Then, model is rotated around slipway curvature centre until the cradle reaches the water level. This happens at 3.86 degree angle. This determines phase 1 ship movement.

Phase 2. Traveling step of 10m is chosen and ship is again rotated step by step. In each travel step following is determined: ship and cradle buoyancy, wetted surface and underwater ship cross-section area projected in the traveling direction. Equilibrium of buoyancy and weight is checked at each step and when buoyancy overcomes weight moment third phase is initiated.

Phase 3. In each travel step following is determined: phase 2 parameters plus buoyancy and weight centre locations, cradle distance from the origin of coordinate system. At each step ship is iteratively adjusted for weight-buoyancy balance. Commonly, this was achieved in 4 to 5 iteration steps.

Phase 4. Once the ship drops off the slipway and is detached from the cradle final wetted surface and surface projected in the sailing direction is determined.

### 4. The problem of ship resistance

As stated earlier, four analytical calculations will be considered and they are denoted as follows:

- Method 1 - Uršić differential equation,
- Method 2 - Uršić energy balance,
- Method 3 - Semyonov differential equation and
- Method 4 - Uljanik calculation.

Ship resistance is important parameter and it is defined within each method. However, estimation of ship resistance is not straightforward. Symbols in the expressions bellow are reproduced as they appear in the literature of origin.

In Method 1 water resistance is defined as [1]:

$$W = k \cdot v^2 \text{ [t]} \quad (1)$$

where  $v$  is a ship speed and coefficient of resistance  $k$ , in  $[\text{t/m}^2]$  is defined by either:

$$k = k_1 = 52.56(0.63A_1 + 0.004A_2),$$

$$k = k_2 = \frac{1}{2}\rho\xi F$$

$$k = k_3 = \xi\Delta^{2/3}$$

where:  $A_1$  is ship and cradle cross section area projected in the direction of traveling,  $A_2$  is wetted ship and cradle surface,  $\rho$  is density,  $F$  is submerged shield area (shields used for slowing down the ship),  $\xi$  is coefficient ranging from 1.2 to 1.5 and  $\Delta$  is ship mass.

First coefficient,  $k_1$ , is referred by Uršić as Benson coefficient and if used according to definition leads to unrealistically high resistance value. Original article referring to definition of Benson coefficient was not available. Second coefficient,  $k_2$ , is used when ship is equipped with shields. Since study-case ship is slowed down by anchors this term is of no use. Even if main frame area is assumed as total shields area, calculated ship resistance is unrealistically high. Third coefficient,  $k_3$ , gives realistic values of ship resistance but it is not clear if it can be used in every launching phase.

In Method 2 water resistance is defined as [1]:

$$W = k \frac{v_2^2 - v_1^2}{2} \text{ [t]} \quad (2)$$

where:  $v_2$  is the speed at the end and  $v_1$  is the speed at the beginning of the interval. Since definition of coefficient  $k$  is omitted in Method 2, Method 1 definitions of  $k$  are assumed.

In Method 3 water resistance is defined as [2]:

$$R = k_s \frac{D_l}{g} s'' + \frac{\rho}{2} C_s W^{2/3} s'^2 \text{ [N]}$$

where:  $k_s$  is added mass coefficient,  $D_l$  is displacement,  $g$  is gravity,  $s''$  is ship acceleration,  $C_s$  is dimensionless coefficient,  $W$  is ship displacement and  $s'$  is ship speed.

In Method 4 water resistance is defined as [3]:

$$W = k \cdot D \cdot v^2$$

where:  $k$  is experience-based coefficient equal to 0.0002 for the ship in concern,  $D$  is ship displacement and  $v$  is ship speed.

Table 1 summarize the results of ship resistance calculation for ship in concern, for each method. Free sailing of the ship in ballast after launching is assumed. No further comment on these findings will be made here as clearing the matter of observed differences is outside the scope of this article.

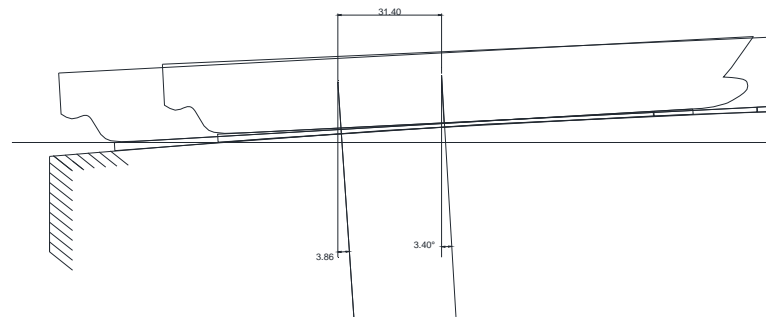
**Table 1** Water resistance calculation by different methods**Tablica 1.** Izračun otpora vode različitim metodama

Method	Water resistance	Resistance coefficient	Value
1	$W = k \cdot v^2$	$k = 52.56(0.63A_1 + 0.004A_2)$ $k = \frac{1}{2}\rho\xi F$ $k = \xi\Delta^{2/3}$	10850 3 120
2	$W = k \frac{v_2^2 - v_1^2}{2}$	-	-
3	$R = k_s \frac{D_l}{g} s'' + \frac{\rho}{2} C_s W^{2/3} s'^2$	$C_s = 0.35$	107
4	$W = k \cdot D \cdot v^2$	$k = 0.0002$	2.94

#### 4. Method 1 - Uršić differential equation [1]

##### 4.1. Phase 1

For the particular case launching phase 1 is illustrated by figure 6.

**Fig. 6** Phase 1 of ship launching**Slika 6.** Prva faza porinuća broda

During that phase sum of forces acting on the ship is:

$$Z = D \cdot \cos(\vartheta) \cdot (\tan(\vartheta) - \mu)$$

Ship speed is calculated as:

$$v = \sqrt{2 \cdot \int_{x_1}^{x_2} b dx}$$

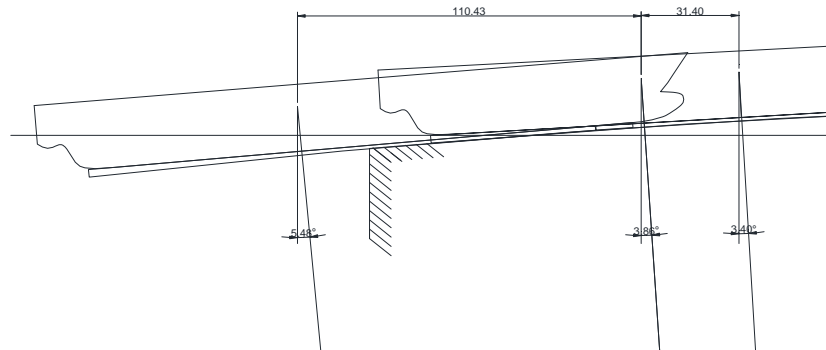
$$b = g \cdot (\sin(\vartheta) - \mu \cdot \cos(\vartheta))$$

where:  $b$  is acceleration,  $\mu$  is friction coefficient and  $\vartheta$  is slipway angle, defined as angle between weight vector and slipway surface normal.

Slipway angle and acceleration are changing during phase 1. In the particular case, slipway angle changes from 3.40 to 3.86 degrees.

#### 4.2. Phase 2

For the particular case launching until phase 2 is illustrated by figure 7.



**Fig. 7** Phase 2 of ship launching

**Slika 7.** Druga faza porinuća broda

As ship enters into water two additional forces appear and sum of forces yields:

$$Z = (D - U) \cdot \sin(\nu) - \mu(D - U) \cos(\nu) - W$$

where:  $U$  is buoyancy,  $W$  is the water resistance and friction  $T$  is:

$$T = \mu \cdot D \cdot \cos(\vartheta)$$

Assuming water resistance to be proportional to ship speed:

$$W = k \cdot v^2$$

following expression is obtained:

$$\frac{d^2x}{dt^2} = (D - U) \cdot (\sin(\nu) - \mu \cos(\nu)) - \frac{k}{D} g \left( \frac{dx}{dt} \right)^2$$

With the following substitutions and integration, ship speed may be calculated [1,3]:

$$Q = \frac{g \cdot (D - U)(\sin \nu - \mu \cos \nu)}{D}$$

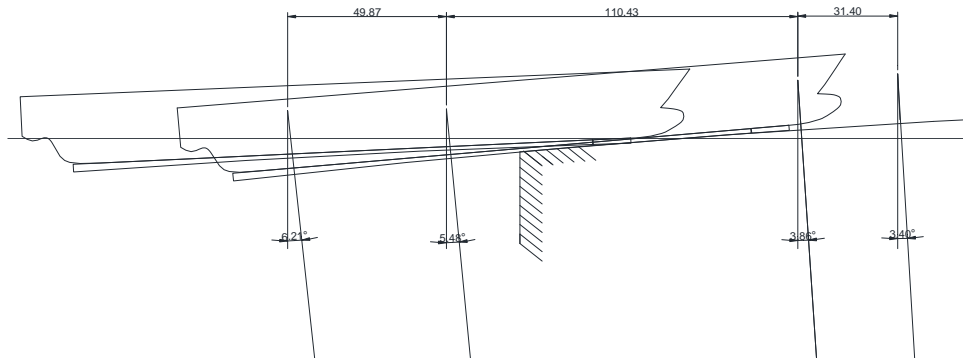
$$P = \frac{k \cdot g}{D}$$

$$v^2 = \frac{2 \int_{x_1}^{x_2} Q \cdot e^{2 \int_{x_1}^{x_2} P dx} dx}{e^{2 \int_{x_1}^{x_2} P dx}}$$

Note that [1] does not indicate integral boundaries. The balance of weight and buoyancy moment must be checked at each calculation step as described in [1]. When they are equal phase 2 is over and phase 3 commences.

#### 4.3. Phase 3

For the particular case launching until phase 3 is illustrated by figure 8.



**Fig. 8** Phase 3 of ship launching

**Slika 8.** Treća faza poruča broda

Sum of forces and ship velocity may be calculated with the phase 2 expressions. Moments are checked in the same way and ship's pitch is adjusted at each step. At the end of phase 3 ship is disconnected from the slipway. Ship speed must be high enough to prevent fore peak hitting the slipway and must be checked using:

$$h = \frac{g \cdot c^2}{2 \cdot v^2}$$

where:  $h$  is dropping height and  $c$  is short path near dropping point.

#### 4.4. Phase 4

In phase 4 ship sails away from slipway and two forces are acting only, inertia and water resistance:

$$\Delta \cdot \frac{d^2 x}{dt^2} = -k \cdot v^2$$

from where:

$$v = v_0 \cdot e^{-\frac{k}{\Delta} x}$$

where:  $v_0$  is ship speed at the end of phase 3 and  $x$  is calculation travel step.

By the term above calculated ship speed is decreasing in time until near full stop.

### 5. Method 2 - Uršić energy balance [1]

This method examines the energy balance throughout launching. Potential energy of the standing ship is converted into kinetic energy during launching and is zero at the end of third phase. Kinetic energy is transformed during launching into friction and water resistance until anchors are finally used to stop the ship.



Following terms describe the loss of potential energy:

$$D \cdot x' \cdot \sin \vartheta$$

the increase of kinetic energy:

$$\frac{1}{2} \cdot \frac{D}{g} \cdot v_2^2 - v_1^2$$

energy lost on friction:

$$\mu(D - U)x' \cos \vartheta$$

and energy lost due to water resistance:

$$W \cdot x'$$

In this way, energy balance during phase 2 and phase 3 is summed as:

$$D \cdot x' \cdot \sin \vartheta = \frac{1}{2} \cdot \frac{D}{g} \cdot (v_2^2 - v_1^2) + \mu(D - U)x' \cos \vartheta + W \cdot x' + U \cdot x' \cdot \sin \vartheta$$

Assuming water resistance to be:

$$W = k \frac{v_2^2 - v_1^2}{2}$$

Ship speed may be determined in the phase 1 as:

$$v_2^2 = \frac{D \cdot x' \cdot \sin \vartheta + 2 \cdot \mu \cdot D \cdot x' \cdot \cos \vartheta + v_1^2 \left( \frac{D}{g \cdot x'} - k \right)}{\left( \frac{D}{g \cdot x'} + k \right)}$$

in the phase 2 and phase 3 as:

$$v_2^2 = \frac{D - U \cdot x' \cdot \sin \vartheta + 2 \cdot \mu \cdot (D - U) \cdot x' \cdot \cos \vartheta + v_1^2 \left( \frac{D}{g \cdot x'} - k \right)}{\left( \frac{D}{g \cdot x'} + k \right)}$$

and in the phase 4 as:

$$v_2^2 = \frac{v_1^2 \left( \frac{D}{g \cdot x'} - k \right)}{\left( \frac{D}{g \cdot x'} + k \right)}$$

Calculation of the ship speed in the phase 4 by this method is very sensitive on the values of coefficient  $k$  and travel step  $x'$ . Findings on this matter may be summarized in the following way: as coefficient  $k$  increases, the choice of travel step has more and more effect on the final results.

## 6. Method 3 - Semyanov differential equation [2]

### 6.1. Phase 1

Sum of forces acting in the phase 1 may be written as:

$$\frac{D}{g}b + D \cdot \sin \vartheta - D \cdot \mu \cdot \cos \beta = 0$$

Assuming the slipway angle is small, acceleration may be expressed as:

$$b = g(\vartheta - \mu)$$

By integration of the term above, following expressions for ship speed is obtained:

$$v = g(\vartheta - \mu)t + v_0$$

### 6.2. Phase 2

Since buoyancy and water resistance moments are negligible in this phase, sum of forces in the direction of ship movement is:

$$\frac{D}{g}b + N \cdot \sin \vartheta - N \cdot \mu \cdot \cos \beta - W = 0$$

$$N = D - \gamma U$$

where:

Ship speed is calculated using expression [2]:

$$v = \sqrt{e^{-n_l} \left[ \frac{2}{3} \cdot g \cdot (\vartheta - \mu) \cdot \left( 1 - \frac{N \cdot x^2 \cdot e^{n_l}}{D} \right) + v_0^2 \right]}$$

$$n_l = C_s \cdot \left( 1 - \frac{N}{D} \right)^{2/3} \cdot \frac{x_l}{\sqrt[3]{\frac{D}{\gamma}}}$$

where:  $\gamma$  is tipping force coefficient.

### 6.3. Phase 3

Forces acting on the ship in the third phase are presented in Figure 9:

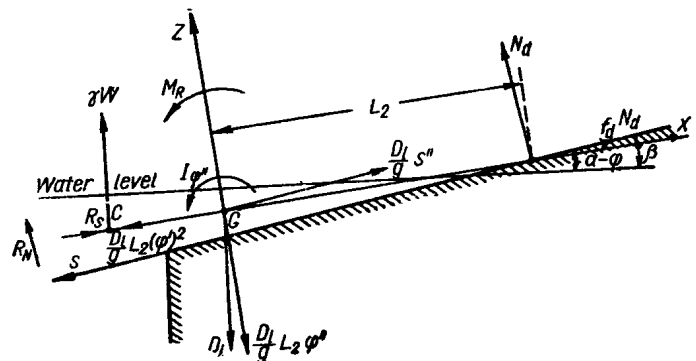


Fig. 9 Forces acting on the ship in phase 3 of launching [2]

Slika 9. Sile koje djeluju na brod u trećoj fazi porinuća [2]

Sum of forces in the direction of ship movement is:

$$-\frac{D}{g}b + \frac{D}{g}L_2 \cdot \varphi'^2 + \frac{D}{g}L_2(\varphi + \vartheta + \alpha)\varphi'' + D\beta - \gamma U\beta - R_s - \mu N = 0$$

Sum of forces in the direction normal to ship movement is:

$$N_d - D + \gamma U + \frac{D}{g}L_2 \cdot \varphi'' + \frac{D}{g}L_2(\varphi + \vartheta + \alpha)\varphi'^2 + R_N = 0$$

Sum of moments around cradle is:

$$-I_y \cdot \varphi'' + R_N + \frac{D}{g}L_2(\varphi + \vartheta + \alpha) \cdot b + \frac{D}{g}L_2^2 \cdot \varphi'' - DL_2 + \gamma U(L_2 - x) - M_R = 0$$

Out of the above equations, following expression for speed calculation is derived:

$$v = \sqrt{e^{-n_l} \left[ 2 \cdot g \cdot (\vartheta - \mu) \frac{N}{D} \left( 1 - \frac{x}{2x_3} \right) + v_0^2 \right]}$$

$$n_l = C_s \cdot \left( 1 - \frac{N}{D} \right)^{2/3} \cdot \frac{x}{\sqrt[3]{\frac{D}{\gamma}}}$$

#### 6.4. Phase 4

In the phase 4 ship inertia and water resistance are in equilibrium:

$$-R - \frac{D}{g}b$$

where water resistance is defined as:

$$R = k_s \frac{D}{g}b + \frac{\rho}{2} C_s \nabla^{2/3} v^2$$

Following expression for ship speed is then derived:

$$v = v_0 \cdot e^{-Px}$$

$$P = \frac{C_s}{2(1 + k_s)} + \frac{1}{\sqrt[3]{\Delta}}$$

### 7. Method 4 - Uljanik calculation

Uljanik shipyard performs launching calculation by in-house made software. For the given input program lists moment and forces, ship acceleration, velocity and traveling distance and other data. In addition, it provides information on slipway and cradle geometry, coefficient of friction, anchors weight etc. Ship speed determined by Uljanik will be compared with previously described three analytical methods.

## 8. DGPS measurement

DGPS measurement was performed by Brodarski institute. Position of the ship was measured by a precise DGPS 8200 HP system from OMNISTAR, Netherlands. In addition to the basic system equipment a notebook computer for real-time processing was installed on site. Approximate position of measurement location is indicated on Figure 10.

Real-time monitoring and automatic recording of data were performed at a sampling frequency of 10Hz (10 record per second). The accuracy of the position measurements at any point during the test was better than  $\pm 1$  m. Output message type were: NMEA 0183, ALM, GBS, GGA, GLL, GRS, GSA, GST, GSV, RMC, VTG, ZDA.

Ship speed,  $v$  during a measurement is defined as:

$$v = l_g / t_g$$

where:  $l_g$  is a beforehand agreed measured sailing distance (over ground/bottom) in beforehand agreed straight course and  $t_g$  is the corresponding time needed.

Ship speed has to be determined by time and position only and was calculated from the measured ship's track. The accuracy of the obtained values for the ship speed during the measurement was  $\pm 0.02$  kn. Described method gives the speed over the ground.

In addition, digital inclinometer was used to record pitch and roll of the ship. Inclinometers is dual axis, y and x direction measurement instrument, with a resolution up to  $0.001^\circ$ , accuracy  $\pm 0.06^\circ$  and measuring range  $\pm 30$  degree.

## 9. Tracker video analysis

Tracker is video analysis software built on Open Source Physics framework [5]. It allows tracking of selected reference point or points as the object moves in space, defined by video frame, and time, defined by video frame rate. Upon the analysis, it provides information on position, velocity and acceleration of object of concern. In addition, it can be calibrated for known distances and can find center of mass tracks in certain cases. Other options include definition of fixed or time-varying coordinate system, scale, origin, tilt etc, Figure 11.

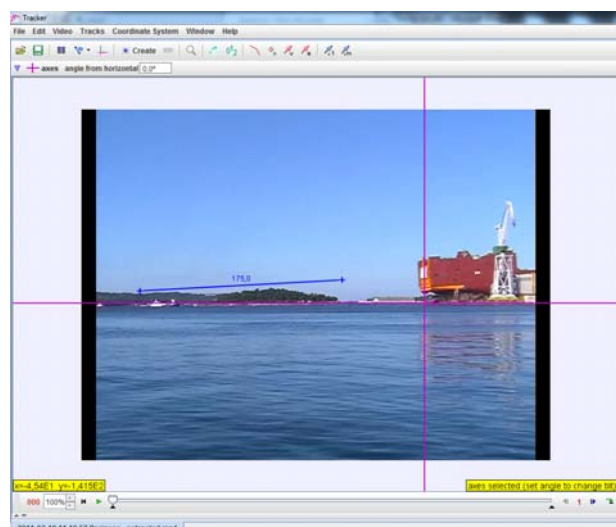


Fig. 11 Tracker screenshot, scale analysis

Slika 11 Prikaz Tracker prozora, određivanje mjerila

On the day of launching camera was set at convenient location and the launching was recorded. Due to limitations of the camera lens only a stern of the ship was in the frame

before the launching commenced, Figure 11. Because of that, reference point is located on the ship stern.

The video recording analysis, i.e. tracking the reference point on the ship, was performed automatically by Tracker according to user instructions. Since it was possible to calibrate physical dimensions, resulting velocity of the ship was obtained directly.

Since DGPS measurement location was not in site throughout the video, another reference spot (on stern) was used. Therefore, direct comparison of the results is not possible in this particular case. Following recommendations for Tracker usage may be given:

- reference point, such as DGPS measurement location or center of the ship mass, should be clearly visible throughout the video recording, i.e. during the entire launching event
- if possible, reference point to be marked on the ship using large, contrast panels
- use 1080p full HD video camera for maximum video recording quality,
- distance from the ship to camera is changing so location and lens focus length must be chosen carefully and according to previous experience.

## 10. Comparison of the results

As mentioned before, ship speed was calculated using three analytical methods. Uljanik ship speed calculation was available too. These are four different methods for prediction of the launching dynamics. Two measurement methods are used to monitor the launching: DGPS measurement and Tracker video analysis. Ship speed during launching for all the methods is presented on Figure 12.

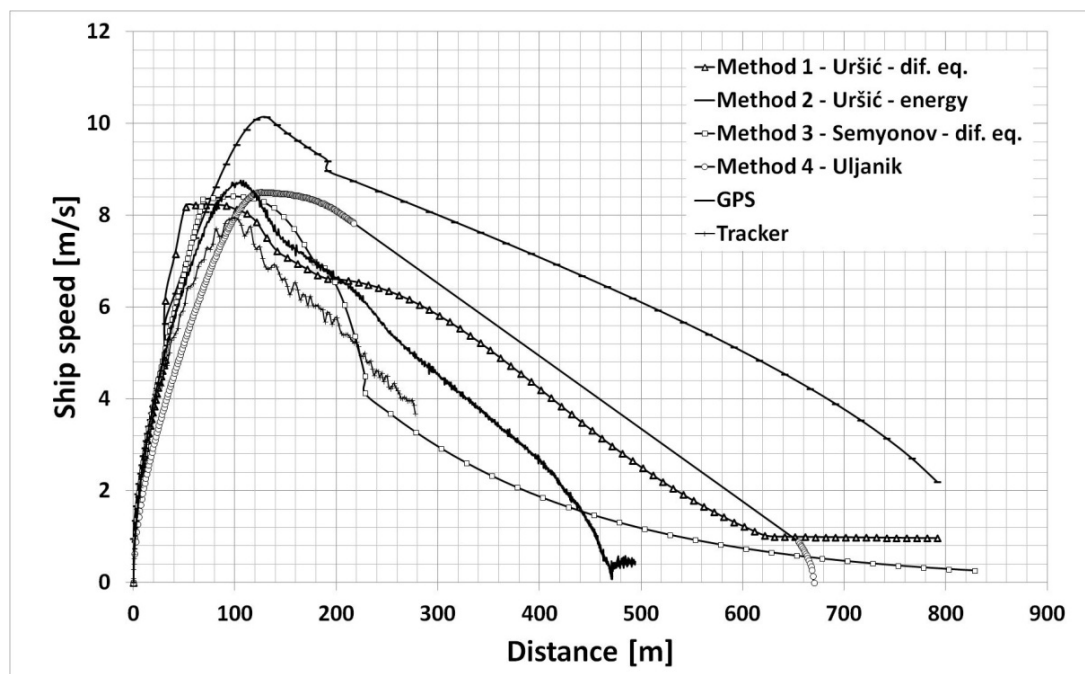


Fig. 12 Comparison of the ship speed calculation and measurements results

Slika 12. Usporedba rezultata izračunatih i izmjerenih brzina broda

GPS measurement detected maximum speed of 8.76 m/s (31.5 km/h, 17 knots) and nearly full stop at approximately 500 meters from initial position. It should be noted that this refer to bow location.

Tracker detected maximum speed of 7.95 m/s and full stop was not recorded as ship stern went out of the video frame. Tracking point is located on the stern.

Three analytical methods refer to center of weight location and results may be expected to be approximately between DGPS and Tracker measurements. This happens to be the case for Method 1 with predicted maximum speed of 8.23 m/s and Method 3 with predicted maximum speed of 8.42 m/s. Method 2 overestimated maximum ship speed with predicted maximum of 10.14 m/s. Uljanik predicted maximum speed of 8.51 which is closest to DGPS measurement.

Calculation of ship's full stop location showed diverse results. Uljanik predicted full stop at approximately 680 meters from initial position. In reality, anchors started to slow down ship earlier, 420 meters from initial location, and were very effective stopping the ship after 60 meters or 480 meters from the initial location. Uljanik calculation is therefore on the conservative side. It should be noted that ship exhibited minor starboard shift during anchor breaking which cannot be noted in DGPS results and does not affect the conclusions.

Inclusion of the breaking force in three analytical methods is not straightforward. However, water resistance seems to be dominant force stopping the ship. Upon looking at DGPS measurements it is obvious that ship was slowing at almost linear rate from 8.76 m/s to approximately 2.2 m/s when anchors started to be effective. This can be seen as slight change in DGPS track slope at 420m.

Method 1 assumes only water resistance as stopping force, changing by quadratic law until speed of 1 m/s and linearly afterwards. Described behavior is obvious on Figure 5. Method 2 enables rather easy inclusion of stopping force (weight) into ship speed calculation [1]. Uljanik declared anchor weight of 40 tons is acting on the ship. If this value is used in Method 2, ship is predicted to stop much later than in reality. Displayed Method 2 graph corresponds to arbitrarily adjusted value of 75 tons anchor weight which gives more realistic results in the phase 4. Partial explanation for this difference may be addressed to complexity of anchors behavior due to uneven sea floor configuration, complex interaction of multiple anchors etc. Measurement of the anchor force is possible as well and would provide good information on the matter. Method 3 uses water resistance as stopping force assuming translatory velocity to decrease to an exponential law as may be seen in the graph.

Main findings and results for all the method mentioned are listed in Table 2: top speed, traveling distance until ship has 1m/s velocity and stopping force(s) included.

**Table 2** Comparison of the results

**Tablica 2.** Usporedba rezultata

Method	Top speed [m/s]	1m/s speed at [m]	Stopping force
M1 Uršić – dif. eq.	8.23	620	water resistance
M2 Uršić – energy	10.14	-	w. resistance + anchors
M3 Semyonov – dif. eq.	8.42	560	water resistance
M4 Uljanik	8.51	660	w. resistance + anchors
GPS	8.76	480	w. resistance + anchors
Tracker	7.95	-	w. resistance + anchors

## 11. Conclusion

Three different analytical methods were used for ship launching calculation and obtained results are compared with shipyard calculation, DGPS measurement and Tracker video record analysis.

Methods based on differential equations provided very good estimation of maximum ship speed, while energy method overestimated maximum speed by 15% margin compared to DGPS measurement maximum speed. Shipyard own calculation provided best prediction of maximum speed.

Estimation of full stop position varied due to different calculation methods but also due to uncertainties related to water resistance and anchor force. However, all the methods provide conservative estimations and are therefore on the safe side.

Analysis pointed out the problem of water resistance estimation. Commonly, water resistance is proportional to ship speed squared. Several expressions are available for calculation of water resistance but results significantly differ. Further research on this topic will follow.

DGPS measurement proved to be a reliable and useful tool for launching analysis due to its remarkable precision. On the other hand, free and simple Tracker software can be used as handy tool for launching monitoring. Many points on ship can be tracked so pitch information may be available as well.

Anchor force determination proved not to be crucial. However, for the given location measurement of the stopping force during launching could be used to calibrate the shipyard calculation.

Further research should be focused on numerical simulation of launching using non-linear, time-domain analysis. Modern fluid-structure interaction is a focus of modern research also due to the increase in computing power. Launching is one such event where complex FSI modelling is possible. However, numerical results must be thoroughly verified and findings in this article could serve that purpose.

## 12. Acknowledgement

Uljanik shipyard provided valuable information about the study-case ship and shipyard launching technique, which is kindly acknowledged.

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